Evaluation Model of Pricing Policy for Urban Transport Networks

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Abstract: The urban transport network consists of urban streets and urban expressway. The toll road system is applied on the urban expressway in Japan. On the other hand, the urban streets are determined to be free of charge. Pricing policy for overall urban transport networks is proposed in the study. According to the congestion charging theory, several road pricing policies have been introduced in the world. Therefore, the road pricing policy on urban transport networks is discussed referring to the present urban expressway toll system. The technique of user equilibrium traffic assignment with variable demand is applied to describe the condition of networks with specific toll system. In particular, the cordon line charging scheme can be proposed from the analysis results of descriptive model.

Keywords: Pricing Policy, Urban Transport Network, Cordon Line, Traffic Assignment

1. INTRODUCTION

The urban expressway and urban streets are determined as urban transport networks. The distance based toll system is applied in Japanese urban expressway. On the other hands, urban streets are available to use without charging. In the study, the road pricing policy overall urban transport network is proposed in addition to the present toll system on urban expressway. The system optimization of urban transport networks with variable demand in traffic assignment corresponds to the optimal condition of congestion toll in the economic theory. Therefore, the algorithm of user equilibrium traffic assignment with variable demand is applied to estimate the social benefit of road pricing on the networks. The descriptive model is proposed to analyse the second best pricing with realistic constraints. In particular, cordon line pricing is analysed involving the urban expressways and urban streets. The impact of the road pricing policy can be measured numerically to show the effectiveness with advanced toll systems.

2. PRICING POLICY ON URBAN TRANSPORT NETWORKS

A distance-based toll system has been introduced since 2012 on the urban expressways such as Hanshin Expressway and Metropolitan expressway in Japan. There are many different values of toll corresponding to the distance between on-ramps and off-ramps.
The current urban expressway toll system is based on the principle of redemption the construction cost. It is different from the congestion toll in economics theory. On the other

hands, urban streets are available to use without charging.
Assuming the single road section, it is considered the optimal condition of congestion toll in economic theory. The social marginal cost (SMC) in the urban transport network and an average travel cost (AC) are shown in Figure 1. In traffic engineering, the average travel cost of vehicles on the link is equivalent to the monetary value of average travel time. Furthermore, the average travel time can be measured by link performance function $t_a(x_a)$ in the traffic assignment.

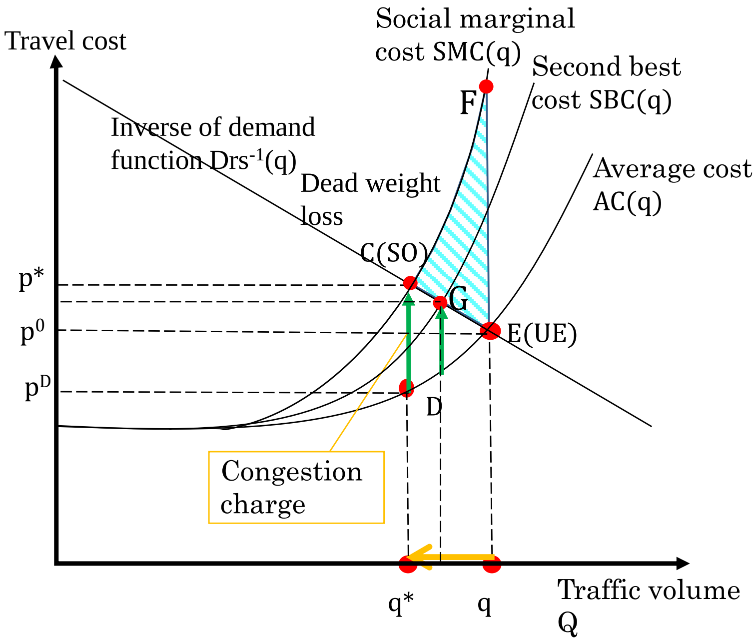

Figure 1. The theory of congestion toll on the road section

The link performance function indicates that the average travel cost is supposed as a function for travel cost for the link traffic volume. In this description, the link travel time is assumed to count as a monetary cost. Therefore, it can be expressed the total travel cost (TC) as traffic volume multiplied by travel time. Furthermore, the social marginal cost (SMC) is equivalent to increase of total travel cost per unit traffic flow. It is mathematically formulated as:

$$SMC(x_a) = \frac{dTC(x_a)}{dx_a} = \frac{d\{t_a(x_a)x_a\}}{dx_a} = t_a(x_a) + x_a\frac{dt_a(x_a)}{dx_a} \quad (1)$$

The x_a is traffic flow on link a, $t_a(x_a)$ is the performance function for link a.
This equation shows a social marginal cost and average travel cost. On the other hand, the demand function can be determined. The inverse demand function $D_{rs}^{-1}(x_a)$ is illustrated in the Figure as well. In the study, the average daily traffic demand can be described with the demand function. If daily variated or time variated traffic demand would be discussed, the detail traffic demand function should be prepared.
The cross section of private travel cost and demand function is shown as point E. In addition, the social optimal point is a point of intersection of the demand curve and social marginal cost curve (point C). Therefore, the traffic volume of user equilibrium without the congestion toll does not correspond to social optimal condition. Therefore, the dead weight loss is observed (area of CEF). The user equilibrium point should be moved to the point C by charging a congestion toll. The purpose of congestion toll is to reduce the dead weight loss as shown CEF in the figure. It corresponds to reduce the traffic volume from q to q^*. The social optimal

cost is equivalent to a congestion charge collected by each link. However, the toll collection of the individual link unit in the urban street is not realistic. Therefore, the pricing method with realistic constraints should be introduced as the second best pricing. The social marginal cost is illustrated as shown SBC(q) in the figure.
The urban transport networks in Keihanshin region in Japan are illustrated in Figure 2. The urban transport network consists of urban expressway and urban streets. Hanshin expressway is the urban expressway with the loop road and several radius routes. The total length of the expressway is counted as 259.1km in 2014.

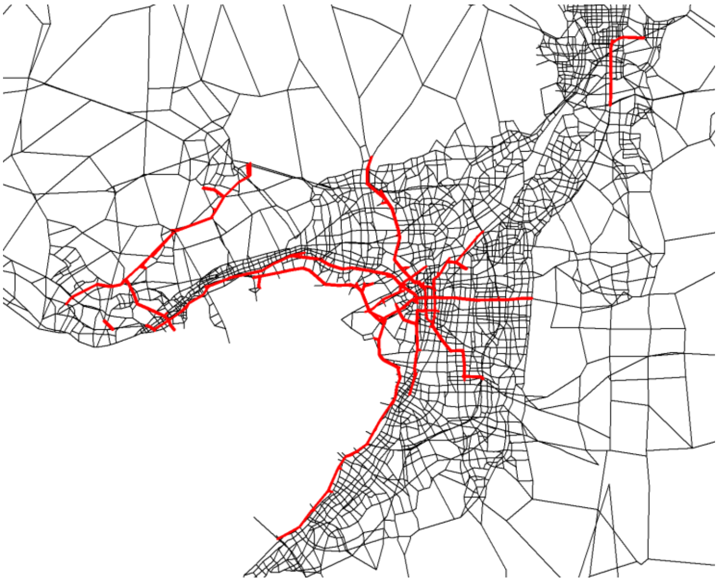

Figure 2. The urban transport networks

3. DESCRIPTIVE MODEL OF URBAN TRANSPORT ANALYSIS

In terms of the impact analysis of the specific distance based toll installation, traffic flow estimation should be required. The user equilibrium (UE) traffic assignment with variable OD demand can be applied with the hyper network representation. The equivalent mathematical problem can be formulated as follows:

$$\min Z = \sum_{a \in A} \int_0^{x_a} t_a(w)dw + \sum_{ij \in \Omega_h} \sum_{l \in K_{ij}} \frac{p_{ij}}{\gamma} f_l^{rs} - \sum_{rs} \int_0^{q_{rs}} D_{rs}^{-1}(u_{rs})du \tag{2}$$

$$\begin{aligned} s.t.& \\ &\sum_{k \in K_{rs}} f_k^{rs} - q_{rs} = 0, \quad \forall rs \in \Omega \\ &x_a = \sum_{k \in K_{rs}} \sum_{rs \in \Omega} \delta_{a,k}^{rs} f_k^{rs}, \quad \forall a \in A \\ &f_k^{rs} \ge 0, \quad x_a \ge 0 \end{aligned}$$

The f_k^{rs} is traffic flow on path k for OD pair r-s, q_{rs} is traffic demand for OD pair r-s, p_{ij} is price of toll for ramp pair i-j, and γ is the value of time.
The objective function is the equivalent to the user equilibrium condition with variable demand.
In the objective function, the first term demonstrated normal UE objective function with fixed OD traffic demand. The second term indicates generalized travel time calculated by

expressway toll and the value of time corresponding to the traffic from on ramp to off ramp. The notation (i, j) described ramp pairs and Ω stands for the set of ramp pairs. Furthermore, the third term demonstrates the sum of the integrals of the inverse demand functions.

The algorithm of UE traffic assignment can be applied to analyse the impact of distance based toll for urban expressway.

The flow diagram of UE traffic assignment model with variable demand is shown in Figure 3. The road network between the origin and the destination is divided by three sub networks. The networks are determined origin to on-ramp for r-i, on-ramp to off-ramp for i-j, and off-ramp to destination for j-s. The shortest path for each network is determined separately. The value of toll should be taken into account for the generalized travel cost for the expressway path. The value of time is applied to determine the equivalent value of travel time of toll. The shortest path for the origin to destination is determined by generalized travel time.

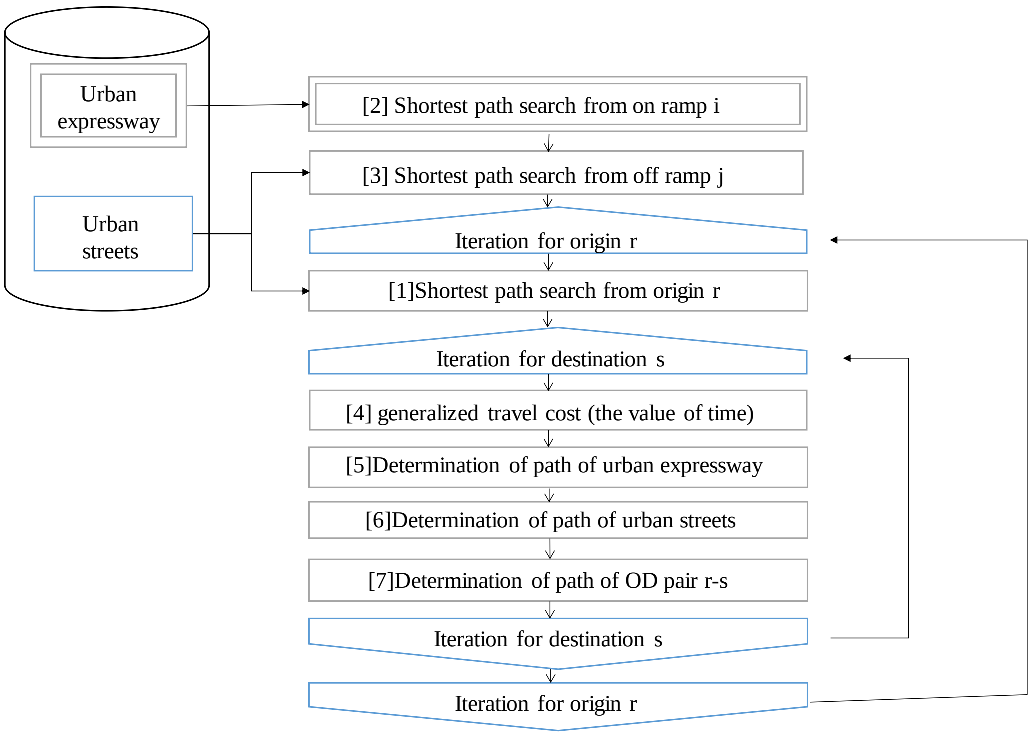

Figure 3. Flow diagram of UE traffic assignment model to analyse the impact of toll

The numerical example is created to describe the balance between the urban expressway traffic and the urban streets shown in Figure 4.

The OD traffic is determined referring to the observed traffic in Hanshin expressway and Keihanshin urban area. The distribution of travel distance for OD traffic is determined similarly to the real distribution.

In terms of variable OD traffic demand of networks, the time variated demand as well as daily variated demand can be assumed. The assumptions correspond to

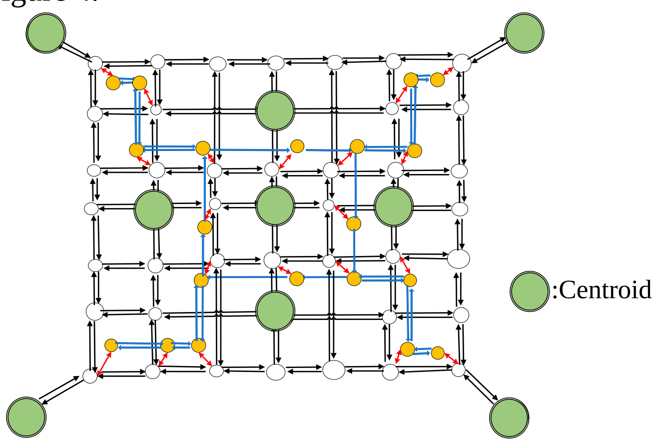

Figure 4. The transport networks for numerical example

the dynamic changing toll systems which are recommended in advanced traffic management. The study aims to determine the basic form of distance based toll as an essential type of toll function. It is expected that the estimation result would be applied similarly to the dynamic toll system as well.

The value of time is determined as 45.78 yen/min/veh according to the cost benefit analysis manual of Japanese ministry of Land, Infrastructure, Transport and Tourism in 2008. The uniform vehicle type as passenger car is assumed for traffic flow estimation. Therefore, travel demand is counted by the number of passenger car trips between OD (origin-destination) pairs. The fixed traffic demand between OD pairs are determined as the initial condition of user equilibrium on the network.

The user equilibrium traffic flow on the network without toll roads is determined corresponding to traffic condition with average cost as the OD travel time.

The dead weight loss can be observed in the gap between the social marginal cost (SMC) and average cost (AC). The traffic assignment model with variable demand should be introduced to describe the relation between the supply and demand of transport service on the networks.

The distance based toll system has been applied for urban expressways in Japan since 2012. The overview of present distance based toll is illustrated in Figure 5. The step function is applied in Hanshin expressway.

This step function is the toll for ordinary vehicle used by the Hanshin Expressway until June 2017. From the understandability of the toll, it was 100 yen unit, but by the consumption tax rate has been revised up ,the toll had been increased to 10 to 30 yen. In addition, the upper limit is set to 930 yen, which is a charge setting preferential treatment for long distance use.

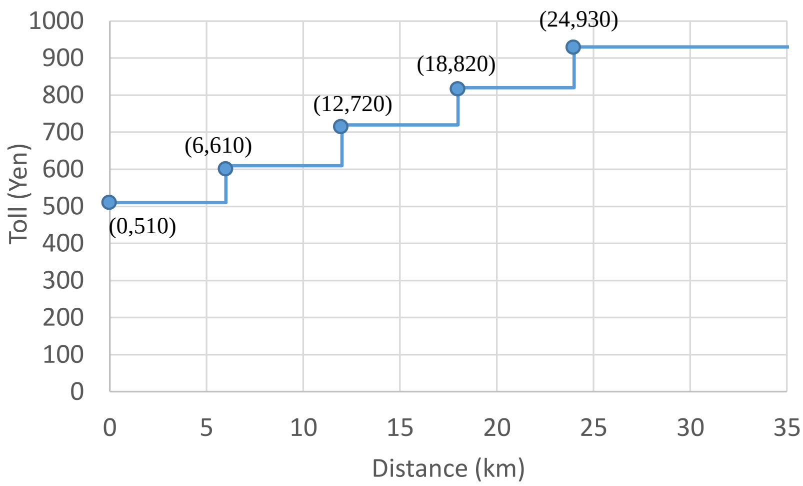

Figure 5. The distance based toll for urban expressway

The price of toll is determined as 510 for the distance less than 6 km. The toll is increased by about 100 yen for each 6 km referring to the function.

The traffic demand Q_{rs} between *r* and *s* can be determined corresponding to generalized travel time for the OD pair as C_{rs}. The linear function is assumed to be an demand function: $Q_{rs}(C_{rs}) = \alpha_{rs} - \beta_{rs} C_{rs}$. Therefore, the inverse of demand function is determined as $Q^{-1}{}_{rs}(q_{rs}) = (\alpha_{rs} - q_{rs})/\beta_{rs}$. The objective function of user equilibrium would be modified with variable demand factors as follows: the parameters such as α_{rs}, β_{rs} can determined for each OD pair corresponding to the fixed demand traffic as shown in Figure 6.

It is confirmed that the numerical example network can be applied to evaluate the traffic conditions instead of real scale urban transport network.

Table 1 summarizes the statistics of traffic flow estimation for real scale network as well as numerical example network.

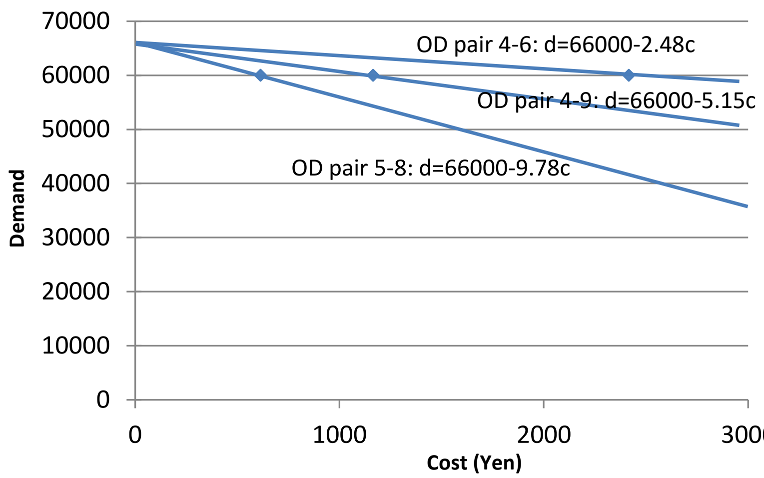

Figure 6. The definition of demand functions

Table 1. The similarity of numerical example to the real scale networks

	Toll revenue (10^6 Yen)	Inflow traffic (10^3 Veh.)	Average distance (km)	Total travel time for expressways (10^3 hr･veh.)	Total travel time for urban streets (10^3 hr･veh.)	Total travel time for overall networks (10^3 hr･veh.)
Numerical example	664	924	18.59	275	2,789	3,065
Real scale network	516	732	17.88	249	7,779	8,028

The essential values for evaluation of traffic condition of urban expressway are estimated similarly such as inflow traffic volume and total travel time on the urban expressway.

According to the network representations, the total travel time of urban streets in the real scale networks is estimated 3.0 times as much as that in the numerical example network.

In the real scale network, it is due to the inclusion of urban streets in areas where the impact of urban expressway is small. Therefore, it is considered restricting the road network to be counted. A limited road network is shown in Figure 7. The total travel time for urban streets is $2{,}618 \cdot 10^3$ hour･vehicle.

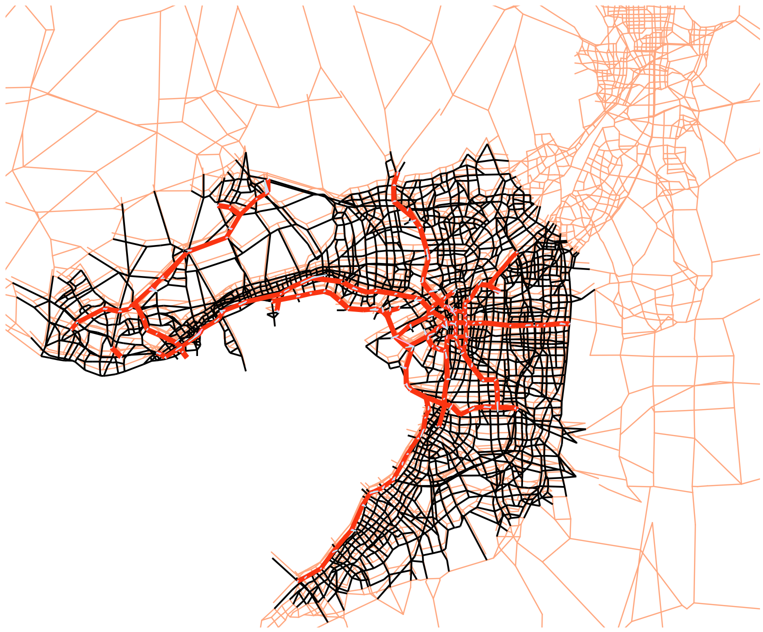

Figure 7. The cutting off urban transport networks

Each index was calculated using the traffic assignment model with above calculation conditions.

The evaluation results are summarized in Table 2.

Table 2. Statistics of user equilibrium with variable demand

Case	Toll revenue (10^6 Yen)	Inflow traffic (10^3 Veh.)	Average distance (km)	Total travel time for expressways (10^3 hr・veh.)	Total travel time for urban streets (10^3 hr・veh.)	Total travel time for overall networks (10^3 hr・veh.)
Free of charge (Case 0)	-	1,518	12.92	678	4,276	4,954
First best prici ng (Case 1)	-	1,565	13.85	453	2,355	2,808
Distance-based toll (Case 2)	664	924	18.59	275	2,789	3,065

The case of free of charge (Case 0) indicated assumption of no toll roads on overall the urban transport network. Even though it is ideal condition, the result corresponds to market equilibrium as point E in Figure 1. The first best pricing case (Case 1) corresponds to the system optimum traffic assignment result. This corresponds to the link based congestion tolls for all urban transport network referring to point C in Figure 1. Therefore, the dead weight loss can be calculated as the difference between two cases such as $2{,}146 \times 10^3$ hr・veh (=4,954-2,808). As the social benefit is counted by the reduction of dead weight loss, the social benefit in Case 2 can be evaluated. Case2 is a result of the step function in figure5. Then the total travel time of roads on overall the urban transport network is between case0 and case1. The relative gain is defined by the following equation.

$$r = \frac{\Delta TT}{\Delta TT_{opt}} = \frac{TT_{zero} - TT}{TT_{zero} - TT_{opt}} \qquad (3)$$

where,

TT : total travel time of overall road network by distance-based toll,

TT_{zero} : total travel time of overall road network by free of charge,

TT_{opt} : total travel time of overall road network by first best pricing.

When the relative gain is 100%, the result is corresponded to the first best pricing.

In the calculation case of the distance-based toll, the relative gain is 88%.

4. COMPARISON OF PRICING POLICY ON URBAN TRANSPORT NETWORK

In this chapter, it is considered pricing including urban streets. As shown in Figure 8, a cordon line is set around the centre of the urban area, and the vehicle coming into the area is charged.

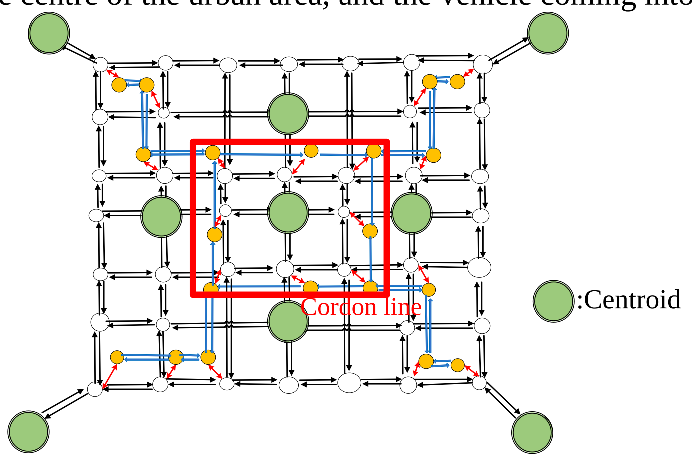

Figure 8. The proposal of cordon line pricing

As cordon pricing, 300 yen and 400 yen are set. The cordon pricing was set with reference to the lower toll price of urban expressway.
The calculation results are shown in Table 3.

Table 3. The comparison of pricing methods

Cordon pricing	Inflow traffic (10^3 Veh.)	Average distance (km)	Total travel time for expressway (10^3 hr・veh.)	Cordon pricing revenue (10^6 Yen)	Total travel time for urban streets (10^3 hr・veh.)	Total travel time for overall networks (10^3 hr・veh.)	Relative gain
300 Yen	1,583	13.42	435	500	2,475	2,911	95.2%
400 Yen	1,616	13.20	431	643	2,530	2,961	92.9%

Because the toll of the urban expressway is assumed to be free, the toll revenue of the urban expressway is 0 yen. The inflow vehicles of urban expressways is larger than that of the case of free of charge shown in Table 2. On the other hand, the total travel time of the urban expressway is smaller than the case of free of charge. The total travel time of the general road is smaller than that of the case of free of charge or distance-based toll. The total travel time of the road network including urban expressways and urban streets is smaller than the case of distance-based toll. Comparing the two cases, the relative gain of 300 Yen is higher. Therefore, 300 yen gives a traffic condition close to the system optimum traffic assignment result.
It is considered the change in traffic volume when cordon pricing is performed. Figure 9 shows the link traffic volume in the case of a distance-based toll and a cordon line pricing.

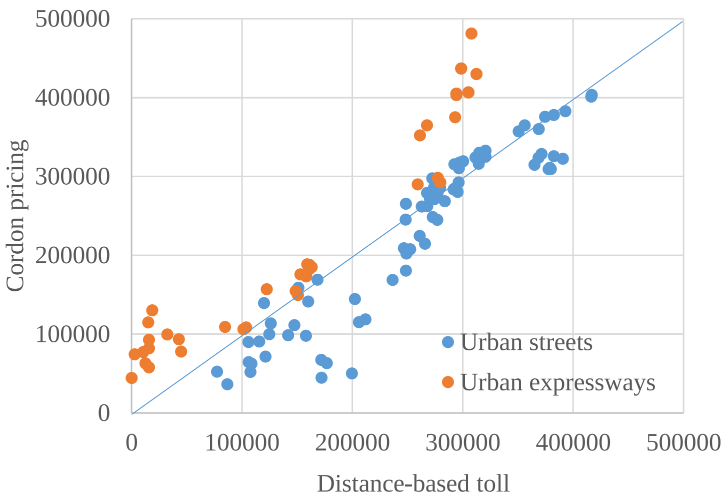

Figure 9. Difference of link traffic volume

Traffic volume is increasing on urban expressway links. No significant increase in traffic volume has been observed on urban street links.

5. CONCLUDING REMARKS

In the study, the road pricing policy overall urban transport network is proposed in addition to the present toll system on urban expressway. The findings of the study can be summarized as follows:

1) The model of user equilibrium traffic assignment with variable demand is applied to estimate the social benefit of road pricing on the networks. The descriptive model is

proposed to analyse the second best pricing with realistic constraints.

2) Based on the formulation of traffic assignment model with variable demand, the model is verified to evaluate charging policy corresponding to various condition settings.

3) A cordon line pricing is analysed involving the urban expressways and urban streets. The impact of the road pricing policy can be measured numerically to show the effectiveness with advanced toll systems.

As a further research, the fluctuation of traffic volume of peak time and off-peak time is considered for cordon line pricing.

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